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Tomas BALEŽENTIS

Lithuanian Institute of Agrarian Economics

Kristiaan KERSTENS

LEM UMR 9221

Zhiyang SHEN

LEM UMR 9221 / z.shen@ieseg.fr

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An Environmental Luenberger-Hicks-Moorsteen Total Factor Productivity Indicator for OECD Countries

Tomas BALEŽENTIS*, Kristiaan KERSTENS**, Zhiyang SHEN**

Abstract: In this paper, we propose a novel environmental Luenberger-Hicks-Moorsteen (LHM) Total Factor Productivity indicator and its decomposition that incorporates a negative externality into the measurement of economic performance. Special cases of a generalized environmental directional distance function are involved in the definition of this LHM indicator and the proposed decomposition. We suggest applying the weak disposability non-parametric environmental technology to implement the proposed decomposition. This LHM indicator decomposes into the three terms representing technical change, technical inefficiency change, and scale inefficiency change. The changes in the environmental TFP for OECD countries are then estimated by applying the data set covering the years from 1990 to 2014. We then show the differences of the proposed framework for the decomposition of the LHM indicator if opposed to some existing ones. The results suggest the proposed approach diverges from the traditional strong disposability non-parametric approach in terms of the cumulative environmental TFP.

Keywords: Total Factor Productivity; Environmental TFP; Luenberger-Hicks-Moorsteen indicator; Weak disposability.

* Lithuanian Institute of Agrarian Economics, V. Kudirkos Str. 18-2, LT-03105 Vilnius, Lithuania
** CNRS-LEM (UMR 9221), IESEG School of Management, 3 rue de la Digue, F-59000 Lille, France. Correspondence to: z.shen@ieseg.fr

1. Introduction

The analysis of total factor productivity (TFP) is important to identify the best practice and the underlying sources of productivity change. Therefore, different TFP indices (using ratios) and indicators (using differences) have been proposed to address the issue. For instance, the Malmquist productivity index (Caves et al., 1982) is probably among the most widely used recent measures of productivity. Yet O'Donnell (2012) argues forcefully that it does not meet the property of completeness (either in a multiplicative sense using ratios or in an additive sense using differences). Furthermore, O'Donnell (2012) states that the Hicks-Moorsteen TFP index proposed by Bjurek (1996) is one of a few indices satisfying the property of completeness. As the ratio-based Hicks-Moorsteen index does not allow for zero values of inputs or outputs, the Luenberger-Hicks-Moorsteen (LHM) TFP indicator has been proposed by Briec and Kerstens (2004). The latter indicator improves on the Luenberger productivity indicator (Chambers, 2002) that fails additive completeness. Therefore, the LHM TFP indicator has the following two appealing features: i) additive completeness (i.e., it serves as a TFP measure), and ii) additive decomposition (i.e., ability to handle zero values). While these productivity indices and indicators have been estimated using traditional parametric specifications of technologies (e.g., Atkinson et al. (2003)), the vast bulk of the literature has opted for a non-parametric approach. This allows to analyze the dynamics of productivity change solely based on technology information and without resorting to data on input and output prices.[1]

Given the environmental considerations raised by such international bodies as the United Nations (2009, 2015), the measurement of green productivity growth has become a topical issue. Accordingly, an important effort has been done to extend the measures of

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[1] In the operations research literature, these non-parametric production technology models go under the moniker DEA (Data Envelopment Analysis): see Farrell, 1957; Charnes et al., 1978; Banker et al., 1984.

productive efficiency and productivity to account for a variety of environmental pressures (see the surveys by Zhou et al., 2008; Dakpo et al., 2016; Sueyoshi et al., 2017).

Managi and Kaneko (2006) applied the LHM TFP indicators proposed by Briec and Kerstens (2004). However, they modelled the undesirable outputs in the same manner as the desirable ones and used the resulting distance functions along with those based on technology involving no undesirable outputs at all. Abad (2015) proposed an environmental generalized LHM TFP indicator, which is based on directional distance functions involving optimization of inputs and undesirable outputs or desirable outputs only. Therefore, the undesirable outputs are essentially treated as strongly disposable inputs.

We depart from that setting by focusing on optimization of inputs and all kinds of outputs separately by means of respective directional distance functions. We thereby assume weak disposability of the undesirable outputs. Furthermore, we propose a decomposition of the environmental LHM indicator allowing one to consider the three terms of technical change, technical inefficiency change, and scale inefficiency change.

The proposed approach relies on the LHM TFP indicator as proposed by Briec and Kerstens (2004). We then extend the indicator following Abad (2015) to accommodate the undesirable outputs and propose a decomposition of the environmental LHM indicator in line with Ang and Kerstens (2017). However, we suggest to model the environmental production technology as proposed by Kuosmanen (2005) by maintaining weak disposability of the undesirable outputs. This proposed framework is applied on a sample of OECD countries. The data cover the period from 1990 to 2014 and allows constructing an environmental production technology including such variables as labor force, capital stock, Gross Domestic Product (GDP), and carbon dioxide emission. Indeed, we compare different settings to demonstrate the applicability of the proposed approach.

The paper proceeds as follows. Section 2 presents the methodology for the analysis of the environmental TFP change. Specifically, the environmental production technology, directional distance functions with corresponding estimators, and decomposition of the environmental LHM indicator are discussed. Section 3 brings together the results of the application of the proposed environmental indicator to the sample of the OECD countries. We compare the proposed approach to the one by Abad (2015) and discuss the patterns in the environmental TFP change prevailing among the OECD countries. We also identify the innovating countries. Finally, Section 4 concludes.

2. Methodology

This section presents the preliminaries for the proposed decomposition of the LHM indicator. First, the environmental technology and the generalized environmental directional distance functions are discussed. Then, we focus on the decomposition of the LHM indicator. Third, the non-parametric production models satisfying the desirable axioms are presented.

2.1. Environmental production technology and directional distance function

We follow a multiple-input multiple-output approach involving both a vector of desirable and a vector of undesirable outputs. Assume that each decision making unit has N inputs (**x**), M desirable outputs (**y**), and J undesirable outputs (**z**). We can define the environmental production possibility set at the time period *t* as follows:

$$T(t) = \left\{ (\mathbf{x}^t, \mathbf{y}^t, \mathbf{z}^t) \in \mathbb{R}_+^{N+M+J} : \mathbf{x}^t \text{ can produce } \left(\mathbf{y}^t, \mathbf{z}^t \right) \right\}. \tag{1}$$

This environmental production technology satisfies usual assumptions such as no free lunch, convexity, strong disposability of inputs and good outputs, the weak disposability of undesirable outputs as introduced by Shephard (1970) and Shephard and Färe (1974), and the null-jointness condition linking desirable and undesirable outputs (e.g., Färe and Grosskopf, 2004). The production axioms no free lunch (A1), convexity (A2), strong disposability of inputs and desirable outputs (A3), weak disposability of outputs (A4), and null-jointness assumption (A5) are defined as follows:

$$\begin{aligned}
&\text{A1}: (0,0,0) \in T(t) \text{ and if } (0,\mathbf{y}^t,\mathbf{z}^t) \in T(t), \text{ then } \mathbf{y}^t = 0 \text{ and } \mathbf{z}^t = 0;\\
&\text{A2}: T(t) \text{ is convex;}\\
&\text{A3}: \text{If } (\mathbf{x}^t,\mathbf{y}^t,\mathbf{z}^t) \in T(t) \text{ and } (\mathbf{x}^t,-\mathbf{y}^t) \leq (\tilde{\mathbf{x}}^t,-\tilde{\mathbf{y}}^t), \text{ then } (\mathbf{x}^t,\tilde{\mathbf{y}}^t,\tilde{\mathbf{z}}^t) \in T(t);\\
&\text{A4}: \text{If } (\mathbf{x}^t,\mathbf{y}^t,\mathbf{z}^t) \in T(t) \text{ and } 0 \leq \theta \leq 1, \text{ then } (\mathbf{x}^t,\theta\mathbf{y}^t,\theta\mathbf{z}^t) \in T(t);\\
&\text{A5}: \text{If } (\mathbf{x}^t,\mathbf{y}^t,\mathbf{z}^t) \in T(t) \text{ and } \mathbf{y}^t = 0, \text{ then } \mathbf{z}^t = 0.
\end{aligned} \qquad (2)$$

The no free lunch (A1) axiom permits for inaction and prevents positive outputs from being produced from zero inputs. Axiom (A2) allows for convexity of the technology. Axiom (A3) implies that production plans dominated by the efficient frontier production plans are feasible: thus, inputs can be wasted and desirable outputs can be destroyed. Axiom (A4) reflects that a unique constraint θ is imposed on both desirable and undesirable outputs allowing for proportional decreases in outputs. The null-jointness assumption (A5) requires that undesirable outputs can only be eliminated if and only if desirable outputs are also at null level.

From an economic point of view, good outputs bring benefits for social welfare and are thus to be increased, while bad outputs generate negative externalities and therefore should be reduced. Obviously, also inputs are scarce and ought to be reduced. This environmental production technology can be represented by the directional distance function following Chambers et al. (1996), Chung et al. (1997) and Färe et al. (2005). A generalized directional distance function simultaneously defining an increase in desirable outputs and a contraction in undesirable outputs and inputs for period $a \in \{t, t+1\}$ with respect to a technology in period $b \in \{t, t+1\}$ can be defined as:

$$D^b(\mathbf{x}^a,\mathbf{y}^a,\mathbf{z}^a;\mathbf{g}_x^a,\mathbf{g}_y^a,\mathbf{g}_z^a) = \max\left\{ \delta \in \mathbb{R}_+ : (\mathbf{x}^a - \delta\mathbf{g}_x^a, y^a + \delta\mathbf{g}_y^t, \mathbf{z}^a - \delta\mathbf{g}_z^t) \in T(t)\right\}, \qquad (3)$$

where $(g_x^t, g_y^t, g_z^t) \geq 0$ are directional vectors of inputs, desirable and undesirable outputs. δ measures the maximum possible increase in desirable outputs and decrease in undesirable outputs and inputs, and $(a,b) \in \{t, t+1\} \times \{t, t+1\}$ allows for the mixed-period directional distance functions.

2.2 The environmental LHM indicator and its decomposition

2.2.1 The environmental LHM indicator

Briec and Kerstens (2004) define the LHM productivity indicator which can be regarded as an additively complete TFP measure following the definition by O'Donnell (2012). The main objective of this paper is to extend the LHM indicator by incorporating the undesirable outputs into the analysis. By doing so, we can offer an approach for the analysis of an environmentally adjusted TFP indicator.

There are several possibilities for incorporating the undesirable outputs into the TFP measure (see, e.g., Dakpo et al., 2016): the undesirable outputs can be regarded as inputs and reduced with inputs simultaneously, or they can enter the model as weakly disposable outputs. We follow the latter approach and opt for increasing the desirable outputs and reducing the undesirable ones simultaneously during the optimization.

The environmental LHM indicator measures the change in the environmental TFP by considering the distances between the frontier and observations for periods t and $t+1$. This is done along the direction of (desirable and undesirable) outputs (keeping input quantities fixed at the base period) and along the direction of inputs (keeping output levels fixed at the base period). To avoid arbitrariness when choosing the base period, the measures are implemented by treating each of the two periods in turn as the base period.

We define the environmental LHM indicator for the base period t as

$$LHM^{t}=\begin{pmatrix}[D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_y^t,\mathbf{g}_z^t)-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})]\\-[D^{t}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0})-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^t,\mathbf{0},\mathbf{0})]\end{pmatrix}, \quad (4)$$

where the first two terms in the brackets capture the distance to the frontier of period t along the direction of desirable and undesirable outputs, whereas the last two terms capture the distance to the frontier along the direction of inputs. Whenever this indicator is higher (resp. lower) than zero, then we observe an environmental TFP gain (resp. loss). Similarly, we define the LHM indicator for the base period $t+1$ as

$$LHM^{t+1}=\begin{pmatrix}[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_y^t,\mathbf{g}_z^t)-D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})]\\-[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0})-D^{t+1}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^t,\mathbf{0},\mathbf{0})]\end{pmatrix}. \quad (5)$$

Then, taking the arithmetic average of indicators given in (4) and (5) one arrives at the LHM productivity change indicator between periods t and $t+1$:

$$\begin{aligned}LHM^{t,t+1}&=\frac{1}{2}(LHM^{t}+LHM^{t+1})\\&=\frac{1}{2}\begin{pmatrix}[D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_y^t,\mathbf{g}_z^t)-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})]\\-[D^{t}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0})-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^t,\mathbf{0},\mathbf{0})]\\+[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_y^t,\mathbf{g}_z^t)-D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})]\\-[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0})-D^{t+1}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^t,\mathbf{0},\mathbf{0})]\end{pmatrix}.\end{aligned} \quad (6)$$

2.2.2 Reducing bad outputs along with inputs: An alternative approach

In an alternative approach, when undesirable outputs are regarded as inputs and reduced along with the inputs simultaneously (see, e.g., Abad 2015), the average of LHM productivity change between periods t and $t+1$ can be defined as:

$$LHM_{\text{bads as inputs}}^{t,t+1}=\frac{1}{2}\begin{pmatrix}[D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_{\mathbf{y}}^{\mathbf{t}},\mathbf{0})-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{0})]\\-[D^{t}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{g}_z^{t+1})-D^{t}(\mathbf{x}_k^t,\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{g}_x^t,\mathbf{0},\mathbf{g}_z^t)]\\+[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^t,\mathbf{z}_k^t;\mathbf{0},\mathbf{g}_y^t,\mathbf{0})-D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{0})]\\-[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{g}_z^{t+1})-D^{t+1}(\mathbf{x}_k^t,\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^t,\mathbf{0},\mathbf{g}_z^t)]\end{pmatrix}, \quad (7)$$

In our empirical application, we compare two possible models: one where bad outputs are regarded as inputs, and one where these are defined as weakly disposable outputs.

2.2.3 A decomposition for the LHM indicator

According to Diewert and Fox (2014, 2017) and the empirical application in Ang and Kerstens (2017), we can decompose the environmental LHM indicator using the output direction (output side) or the input direction (input side) into the following three components:

$$LHM^{t,t+1} = TEC^{t,t+1} + TP^{t,t+1} + SEC^{t,t+1} \quad (8)$$

where *TEC* is technical inefficiency change, *TP* is technological change, and *SEC* is scale inefficiency change.

with respect to the observation from period $t+1$. Indeed, $TP^{t,t+1} > 0$ (resp. $TP^{t,t+1} < 0$) indicates technical progress (resp. regress).

Finally, the *SEC* component shows the residual if the evaluated production plan is getting closer to or further away from the most productive scale size as represented by the change in the gradient of the frontier:

$$\begin{aligned} & LHM_{output}^{t,t+1} - TEC_{output}^{t,t+1} - TP_{output}^{t,t+1} \\ & = \frac{1}{2}\begin{pmatrix} [D^t(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1}) - D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})] \\ -[D^t(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0}) - D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{g}_x^{t},\mathbf{0},\mathbf{0})] \\ +[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t}) - D^{t+1}(\mathbf{x}_k^{t},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t})] \\ -[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0}) - D^{t+1}(\mathbf{x}_k^{t},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t},\mathbf{0},\mathbf{0})] \end{pmatrix}, \end{aligned} \tag{11}$$

where the first four terms measure the gradient of the frontier for period t in the region spanned by x^t and x^{t+1}, whereas the last four terms measure the gradient of the frontier for period $t+1$ in the same region.

Following Diewert and Fox (2017) and Ang and Kerstens (2017), expression (11) can be rewritten by using the translation property of the directional distance function:

$$\begin{aligned} SEC_{output}^{t,t+1} = & \frac{1}{2}\begin{pmatrix} [D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t,*},\mathbf{z}_k^{t,*};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t}) - D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t+1,**},\mathbf{z}_k^{t+1,**};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})] \\ -[D^t(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0}) - D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{g}_x^{t},\mathbf{0},\mathbf{0})] \end{pmatrix} \\ & + \frac{1}{2}\begin{pmatrix} [D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t,**},\mathbf{z}_k^{t,**};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t}) - D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1,*},\mathbf{z}_k^{t+1,*};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})] \\ -[D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t+1},\mathbf{0},\mathbf{0}) - D^{t+1}(\mathbf{x}_k^{t},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{g}_x^{t},\mathbf{0},\mathbf{0})] \end{pmatrix}, \end{aligned} \tag{12}$$

where

$$\begin{aligned} \left(\mathbf{y}_k^{t,*},\mathbf{z}_k^{t,*}\right) &= \left(\mathbf{y}_k^{t},\mathbf{z}_k^{t}\right) + D^t(\mathbf{x}_k^{t},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t})(\mathbf{g}_y^{t},\mathbf{g}_z^{t}), \\ \left(\mathbf{y}_k^{t+1,*},\mathbf{z}_k^{t+1,*}\right) &= \left(\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1}\right) + D^t(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})(\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1}), \end{aligned} \tag{13}$$

and

$$\begin{aligned} \left(\mathbf{y}_k^{t,**},\mathbf{z}_k^{t,**}\right) &= \left(\mathbf{y}_k^{t},\mathbf{z}_k^{t}\right) + D^{t+1}(\mathbf{x}_k^{t},\mathbf{y}_k^{t},\mathbf{z}_k^{t};\mathbf{0},\mathbf{g}_y^{t},\mathbf{g}_z^{t})(\mathbf{g}_y^{t},\mathbf{g}_z^{t}), \\ \left(\mathbf{y}_k^{t+1,**},\mathbf{z}_k^{t+1,**}\right) &= \left(\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1}\right) + D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1})(\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1}). \end{aligned} \tag{14}$$

Note that expression (13) defines the efficient values of outputs, $\left(\mathbf{y}_k^{t,*},\mathbf{z}_k^{t,*}\right)$ and $\left(\mathbf{y}_k^{t+1,*},\mathbf{z}_k^{t+1,*}\right)$, for respective levels of input use at different time periods with respect to technology of period t. Similarly, expression (14) defines the optimal output levels, $\left(\mathbf{y}_k^{t,**},\mathbf{z}_k^{t,**}\right)$ and $\left(\mathbf{y}_k^{t+1,**},\mathbf{z}_k^{t+1,**}\right)$, relative to technology of period $t+1$. Therefore, expression (11) defines the dynamics in the shape of the frontiers as represented by their efficient points.

2.3 Estimation strategy

The directional distance function can be estimated by employing parametric or non-parametric approaches. We apply the non-parametric approach which allows for estimation of the production frontier without specifying a specific functional form and which allows imposing a priori assumptions like monotonicity and convexity on the technology. Kuosmanen (2005) and Kuosmanen and Podinovski (2009) propose an improved weak disposability model which also maintains convexity of the production possibility set. Following Kuosmanen and Podinovski (2009) we can define the non-parametric environmental production technology as follows:

$$\begin{aligned} \hat{T}(t)=\Big\{(\mathbf{x}^t,\mathbf{y}^t,\mathbf{z}^t)\in\mathbb{R}_+^{N+M+J}:\ & \sum_{k=1}^{K}\theta_k\lambda_k y_k^{m,t}\geq y^{m,t},\ \forall m=1,\cdots,M; \\ & \sum_{k=1}^{K}\theta_k\lambda_k z_k^{j,t}=z^{j,t},\ \forall j=1,\cdots,J; \\ & \sum_{k=1}^{K}\lambda_k x_k^{n,t}\leq x^{n,t},\ \forall n=1,\cdots,N;. \\ & \sum_{k=1}^{K}\lambda_k=1\,; \\ & \lambda_k\geq 0,\ \forall k=1,\dots,K; \\ & 0\leq\theta_k\leq 1,\ \forall k=1,\dots,K\Big\}, \end{aligned} \tag{15}$$

where θ_k are the observation-specific abatement factors.

To calculate the LHM indicator in expressions (4) and (5) and its components, one needs to solve a series of linear programs. Here we present only the two particular cases where input-output vectors from period $a \in \{t, t+1\}$ are compared against technology of period $b \in \{t, t+1\}$ as defined by the corresponding output or input directional distance functions. Let us assume there are K decision making units (DMUs) indexed by $k = 1, 2, \ldots, K$. The input-output vectors of these units then serve to construct an empirical frontier. Specifically, the output directional distance function $D^b(\mathbf{x}^a, \mathbf{y}^a, \mathbf{z}^a; \mathbf{0}, \mathbf{g}_y^a, \mathbf{g}_z^a)$ is obtained via solving the following problem:

$$
\begin{aligned}
& D^b(\mathbf{x}^a, \mathbf{y}^a, \mathbf{z}^a; \mathbf{0}, \mathbf{g}_y^a, \mathbf{g}_z^a) = \max_{\delta, \lambda_k, \sigma_k} \ \delta \\
s.t. \ & \sum_{k=1}^{K} \lambda_k y_k^{m,b} \geq y^{m,a} + \delta g_y^{m,a}, \quad m = 1, \ldots, M; \\
& \sum_{k=1}^{K} \lambda_k z_k^{j,b} = z^{j,a} - \delta g_z^{j,a}, \quad j = 1, \ldots, J; \\
& \sum_{k=1}^{K} (\lambda_k + \sigma_k) x_k^{n,b} \leq x^{n,a}, \quad n = 1, \ldots, N; \qquad \text{(LP1)} \\
& \sum_{k=1}^{K} (\lambda_k + \sigma_k) = 1; \\
& \lambda_k \geq 0, \quad k = 1, \ldots, K; \\
& \sigma_k \geq 0, \quad k = 1, \ldots, K.
\end{aligned}
$$

where $\boldsymbol{\lambda}$ and $\boldsymbol{\sigma}$ are the vectors of intensity variables, δ is the value of the output directional distance function showing maximum expansions in good outputs and reductions in bad outputs for direction defined by $(\mathbf{0}, \mathbf{g}_y^a, \mathbf{g}_z^a)$. The input directional distance function $D^b(\mathbf{x}^a, \mathbf{y}^a, \mathbf{z}^a; \mathbf{g}_x^a, \mathbf{0}, \mathbf{0})$ is obtained via solving the following problem:

$$
\begin{aligned}
& D^{b}(\mathbf{x}^{a},\mathbf{y}^{a},\mathbf{z}^{a};\mathbf{g}_{x}^{a},\mathbf{0},\mathbf{0}) = \max_{\phi,\lambda_k,\sigma_k} \ \phi \\
s.t.\ & \sum_{k=1}^{K}\lambda_k y_k^{m,b} \geq y^{m,a},\ \forall m=1,\cdots,M; \\
& \sum_{k=1}^{K}\lambda_k z_k^{j,b} \leq z^{j,a},\ \forall j=1,\cdots,J; \\
& \sum_{k=1}^{K}(\lambda_k+\sigma_k)x_k^{n,b} \leq x^{n,a}-\phi g_x^{n,a},\ \forall n=1,\cdots,N; \qquad \text{(LP2)} \\
& \sum_{k=1}^{K}(\lambda_k+\sigma_k)=1; \\
& \lambda_k \geq 0,\ \forall k=1,...,K; \\
& \sigma_k \geq 0,\ \forall k=1,...,K;
\end{aligned}
$$

where $\boldsymbol{\lambda}$ and $\boldsymbol{\sigma}$ are the vectors of intensity variables and ϕ is the value of the input directional distance function denoting the maximum contraction in inputs for direction defined by $(\mathbf{g}_x^a,\mathbf{0},\mathbf{0})$ at period $a \in \{t,t+1\}$.

Full efficiency is represented by zero values of δ (or ϕ) whereas positive values indicate inefficiency. The direction vector *g* is chosen for each of the evaluated DMUs and the optimal scores are expressed as a percentage of the chosen direction vectors. The inequality in the constraint on the bad outputs indicates that the shadow prices of bad outputs must be positive and, hence, that bad outputs are regarded as having a social costs (see Leleu (2013) for details). Note that the estimation of the LHM indicator also requires mixing the periods of input and output vectors in certain instances, yet these calculations are straightforward generalizations of the linear programming models given above.

3. Data and empirical results

The proposed methodology is applied on the data set comprising production and environmental variables for the OECD countries. This section, therefore, presents the data and results. The proposed approach is also contrasted to the proposal by Abad (2015) (see subsection 2.2.2) and to the LHM TFP indicator ignoring undesirable output.

3.1 Data set

This data cover 34 OECD countries including Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Korea, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The period covered are the years from 1990 to 2014.

We use two inputs, namely labor force and capital stock. There is one desirable output, GDP, representing the level of economic activity. In addition, there is one undesirable output, carbon dioxide emission, quantifying the environmental pressure. The labor force is measured as the number of persons (in millions) employed in each of the 34 OECD countries. For the capital stock, the perpetual inventory method is applied. The latter variable is measured in millions of 2011 US dollars thanks to the application of purchasing power parities. The real GDP is measured in millions of 2011 US dollars by employing purchasing power parities. The two inputs and GDP come from the Penn World Table 9.0 (Feenstra et al., 2015) provided by the University of Groningen. The carbon dioxide emission is measured in millions of tons. The carbon emission considered is that from fuel combustion and is based on a sectoral approach (International Energy Agency, 2016).

Table 1 presents the descriptive statistics and average growth rates for inputs and outputs. As one can observe, the capital input shows the highest average growth rate of over 4% per annum on average. GDP comes next with a growth rate of some 2.67% p.a. Labor force grows only at 0.89% p.a. Finally, the carbon dioxide emission shows the lowest rate of growth of 0.42% p.a. These figures imply an increasing accumulation of capital within the

OECD countries which exceeds the rate of GDP growth. This possibly implies a negative change in TFP prevailing in certain regions.

Table 1 about here

3.2 Results

To demonstrate the main feature of the proposed model for the measurement of the environmental LHM TFP, we contrast it to two alternative options: (i) we treat carbon dioxide emission as an input in the LHM TFP indicator, and (ii) we apply the model without carbon dioxide emission in the LHM TFP indicator. Figure 1 summarizes results for the cumulative growth for these three LHM models involving different assumptions on the treatment of the undesirable output. It is easy to note that the proposed model relying on the assumption of weak disposability diverges from the other two models, where carbon dioxide emission is either treated as an input or ignored. While the period of 1990-2002 enjoys a similar upward trend in cumulative TFP change for all the approaches, later on the proposed approach tends to yield much lower cumulative growth rates opposed to the two options without weakly disposable outputs.

Figure 1 about here

The results in Figure 1 suggest that the two alternative models yield more optimistic results for the whole period of 1990-2014 compared to the proposed environmental LHM TFP approach. Indeed, the decline in the TFP obtained for the period 2003-2014 based on the proposed framework yields a net decrease in the cumulative TFP when looking over the whole period from 1990-2014, whereas the other two alternative approaches show an increase in the cumulative TFP. Specifically, cumulative average TFP change based on the proposed approach corresponds to the average decrease in the TFP of 0.15% p.a. By contrast, the model with no undesirable output resulted in the average rate of growth of 1.07% p.a. Similarly, the model treating carbon dioxide emission as an input gets an average rate of growth of 1.29% p.a. These findings confirm the differences of the proposed methodology compared to the Abad (2015) approach and the model without carbon dioxide emissions.

Up to now, we have looked into the differences across the different approaches towards measurement of the dynamics in the environmental LHM TFP indicator at the aggregate level. We now pick by way of example some specific countries with different trends in the environmental TFP if measured by these same approaches. The countries we select are the US and France and the results are depicted in Figure 2. More specifically, we now focus on our proposed approach where carbon dioxide emission is treated as an undesirable output and the approach in line with Abad (2015) where the same emission is treated as a strongly disposable input.

<u>Figure 2 about here</u>

It turns out that the trends in the change of the environmental TFP are reversed depending on the approach employed. By applying our proposed approach, France shows a negative cumulative change in the environmental TFP corresponding to an average rate of growth of -0.88% p.a. Similarly, the US shows a downward trend in the cumulative environmental TFP corresponding to the average rate of growth of -0.21% p.a. These trends are reversed if the measurement is based upon the approach where carbon dioxide emission is treated as an input. France and the US now switch to a positive cumulative change in the environmental TFP with the associated average rates of growth being 1.06% p.a. and 0.80%

p.a., respectively. Therefore, the results considering the change in the environmental LHM TFP indicators are highly impacted by the choice of the modelling approach. This holds at both individual and aggregate levels.

Furthermore, we have applied the additive decomposition of the environmental LHM TFP indicator (see (8)). Therefore, we decompose the cumulative growth in the environmental TFP into the three terms, i.e., technological change, technical inefficiency change, and scale inefficiency change. By doing so, we can identify the underlying sources of growth in the green TFP for the OECD countries. Figure 3 presents these decomposition results at the aggregate level.

Figure 3 about here

We start with discussing technical efficiency change (*TEC),* then we move to technological change (*TP),* and then we end with scale efficiency change (*SEC).* The technical inefficiency change component (TEC) follows a negative trend after the period of 1998-1999 and becomes negative soon afterwards. This decline in TEC is represented by a negative rate of growth of -0.33% p.a.

The technical change component (TP) reveals a positive trend implying that countries tend to increase their environmental TFP by moving towards the efficiency frontier. Indeed, the average rate of growth is 0.84% p.a. Looking at the trend in the dynamics of this particular component reveals that TFP gains are mainly achieved during the period 1990-2002, while the subsequent years see little serious TFP gains due to technical change.

The scale inefficiency change (SEC) component has been following a clearly negative trend throughout the whole period 1990-2014. Specifically, the average rate of growth was -0.67% p.a. Such a trend clearly indicates a deviation away from the most productive scale size represented by a constant returns to scale region within a technology. Thus, both the smallest and largest economies should seek to increase their environmental LHM TFP by optimizing their scale of operations.

To reveal the components of change in the environmental LHM TFP indicator across different countries, Table 2 presents the country-specific results. Countries are listed in simple alphabetic order. As a general observation, the average rate of growth in the environmental LHM TFP indicator, as measured on the weakly disposable technology, varies considerably across the OECD countries. The highest value is observed for Poland (2.73% p.a.), whereas Turkey is attributed with the lowest value of -2.4% p.a. Also observe that the overall average growth rate of LHM TFP is weakly negative and that the only positive contribution is due to technological change.

Table 2 about here

Poland, Finland, Slovakia, Sweden, Australia, Italy, Norway, Denmark, and Belgium comprise the best-performing group, where the average rate of growth in the environmental TFP is 0.71% p.a. at least. Most of these countries rely on gains from the technical progress. The relatively more recently developed countries like Poland and Slovakia appear as exceptions in this pattern. Indeed, their growth in the environmental TFP is mainly determined by technical efficiency gains and scale efficiency changes respectively.

Another group of countries, viz. Ireland, Israel, Czech Republic, Greece, Canada, Spain, Austria, and New Zealand, show higher-than-average rates of growth in the environmental LHM TFP. Within this group, the rates of growth varied in between 0.26% p.a. for Israel and -0.13% p.a. for New Zealand. Note that most of these countries struggle with a negative change in technical efficiency as well as in scale efficiency, except Israel.

Technological change remains the sole positively contributing component, except for New Zealand.

The Netherlands, the United States, Germany, Hungary, Luxembourg, Switzerland, Iceland, and Republic of Korea fall within a category of worse-performing countries in terms of growth in the environmental TFP. Specifically, the average growth in TFP ranges in between 0.2% p.a. for the Netherlands and -0.57% p.a. for the Republic of Korea. Indeed, most of the countries falling within this particular group are highly industrialized. Technological change is positive, except for the Republic of Korea. With the exception for Hungary, Luxembourg and the Republic of Korea, there is also a negative contribution of the scale inefficiency component.

The worst-performing group of countries encompasses Portugal, France, the United Kingdom, Slovenia, Japan, Estonia, Mexico, Chile, and Turkey. Indeed, the average rate of growth in the environmental TFP falls below the value of -0.74% p.a. Within this group, Estonia is the only country exhibiting an increase in the LHM TFP indicator due to gains in scale efficiency.

In many cases, losses in the LHM TFP indicator due to scale inefficiency change exceed the gains from improvements in technical efficiency. Therefore, there seems to be some increasing misallocation of production factors among these OECD countries. However, these results are based on the dynamic change in TFP. It is needed to look at the levels of efficiency to determine changes in the ranking of these countries in terms of the transformation of inputs into outputs.

The use of this TFP framework is also useful for the identification of the innovative countries. Indeed, we seek to identify the innovative OECD countries which push the production frontier upwards towards the region associated with higher TFP. Following Färe et al. (1994) and Beltran-Estevea and Picazo-Tadeo (2017), the innovative countries can be identified by considering three criteria simultaneously: (i) a positive technical change must be observed (i.e., $TP^{t,t+1} > 0$); (ii) the production plan for period $t+1$ must be infeasible with respect to the technology of period t (i.e., $D^{t}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1}) < 0$); and (iii) the production plan for period $t+1$ must be efficient with respect to the technology of period $t+1$ (i.e., $D^{t+1}(\mathbf{x}_k^{t+1},\mathbf{y}_k^{t+1},\mathbf{z}_k^{t+1};\mathbf{0},\mathbf{g}_y^{t+1},\mathbf{g}_z^{t+1}) = 0$). Table 3 presents an exhaustive summary of all instances of these innovative countries for the period 1990-2014. In particular, we report the number of time periods a certain country has been identified as being innovative along with the first and the last periods this occurs. Note that these results are based on the environmental LHM TFP indicator as proposed in this contribution.

Table 3 about here

The United States appear as an innovative country for the highest number of times (19 times during 1990-2014). Then follows France with 16 cases. Norway, Switzerland, and Turkey appear as innovative countries for 14 times. Note that all of these listed countries virtually cover the whole period and can be regarded as persistent innovators. Iceland shows a lower number of occurrence (10 times), yet these are also scattered over the whole period of 1990-2014. Countries such as Poland and Germany appear as innovators around the period of 2006-2007 and have remained in that position until 2014. Finally, countries such as Ireland, Japan, Estonia, Luxembourg, Mexico, Chile, and the United Kingdom appear as innovative for a certain time period but cease to be so afterwards. Therefore, one could identify successful cases of persistent innovations and less successful instances, where such a status has been lost.

4. Conclusions

In this contribution, we have proposed an environmental Luenberger-Hicks-Moorsteen indicator and its decomposition. The directional distance functions are defined so that the input distance function seeks to minimize the use of inputs, whereas the output distance function seeks to expand (resp. contract) the production of desirable (resp. undesirable) outputs. The change in the environmental TFP is then factorized with respect to technical progress, technical inefficiency change, and scale inefficiency change.

The application of the proposed LHM indicator for a sample of the OECD countries over the period 1990-2014 shows that this new framework yields different results compared to models where the undesirable outputs are treated as inputs or remain ignored. Therefore, the proposed approach merits further applications in different domains to obtain more robust and conclusive results regarding the environmental performance, and particularly, the dynamics in the environmental TFP. Indeed, the differences in the results between the different approaches are obtained at both the aggregate level and at the country level (as exemplified by France and the US).

Focusing on the empirical example, the cumulative average TFP change for the whole sample based on the proposed approach corresponds to an average decrease in the LHM TFP of 0.15% p.a. The components of technical inefficiency change and scale inefficiency change are those negatively affecting the growth in the environmental TFP. Indeed, the scale inefficiency component follows a persistently negative trend throughout 1990-2014 thus indicating an increasing misallocation of the production factors among the OECD countries. The United States appeared as an innovative country for the highest number of times, followed by France, and then Norway, Switzerland, and Turkey follow suit. These results can be applied to identify the best practice as well as the sources of changes in the environmental TFP.

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Table 1. Descriptive statistics for input and outputs variables

Variable	**Unit**	**Mean**	**Std. Dev.**	**Min**	**Max**	**Trend**
Labor Force	million	15.4	25.6	0.1	148.5	0.89%
Capital Stock	million $	3565222.2	7233209.3	31385.2	52849892.0	4.06%
GDP	million $	1089733.8	2321939.6	7493.4	16490883.0	2.67%
CO_2	million tons	354.4	898.4	1.9	5702.3	0.42%

Table 2. Annual growth rates of cumulative LHM indicator and its components, 1990-2014

Country	**LHM**	**TEC**	**SEC**	**TP**
Australia	0.89%	-0.28%	-0.27%	1.44%
Austria	-0.12%	-1.11%	-1.59%	2.57%
Belgium	0.71%	-1.43%	-0.64%	2.77%
Canada	0.04%	-0.21%	-0.21%	0.46%
Chile	-2.35%	-0.47%	-0.82%	-1.06%
Czech Republic	0.06%	-0.39%	-0.81%	1.25%
Denmark	0.73%	-0.87%	-0.84%	2.44%
Estonia	-1.24%	-1.64%	3.85%	-3.45%
Finland	1.40%	-1.03%	-1.00%	3.43%
France	-0.88%	0.00%	-1.76%	0.88%
Germany	-0.21%	0.67%	-1.53%	0.65%
Greece	0.05%	-0.55%	-1.19%	1.79%
Hungary	-0.27%	-0.45%	0.08%	0.10%
Iceland	-0.47%	0.00%	-1.02%	0.55%
Ireland	0.26%	-0.69%	-0.05%	1.00%
Israel	0.21%	-0.79%	0.11%	0.90%
Italy	0.83%	-0.37%	-0.25%	1.45%
Japan	-1.18%	-0.18%	-0.86%	-0.14%
Luxembourg	-0.30%	-2.29%	1.37%	0.61%
Mexico	-1.91%	0.27%	-2.29%	0.12%
Netherlands	-0.20%	-0.22%	-0.80%	0.83%
New Zealand	-0.13%	-0.19%	0.17%	-0.12%
Norway	0.78%	0.11%	-1.64%	2.30%
Poland	2.73%	2.53%	0.22%	-0.02%
Portugal	-0.74%	-0.62%	-1.87%	1.74%
Rep. of Korea	-0.57%	-0.65%	0.10%	-0.01%
Slovakia	1.03%	0.69%	1.13%	-0.79%
Slovenia	-1.16%	-1.28%	-1.22%	1.34%
Spain	-0.01%	-0.21%	-0.63%	0.83%
Sweden	0.91%	0.41%	-1.74%	2.24%
Switzerland	-0.38%	-0.04%	-2.23%	1.89%
Turkey	-2.40%	0.00%	-2.05%	-0.35%
United Kingdom	-1.13%	0.09%	-1.31%	0.09%
United States	-0.21%	0.00%	-1.18%	0.97%
Average	-0.15%	-0.33%	-0.67%	0.84%

Note: the stochastic annual rates of growth are given.

Table 3. The numbers of time periods countries appear as innovators and the associated initial and last time periods, 1990-2014

Country	Number of periods	Initial period	Last period
United States	19	1990-1991	2013-2014
France	16	1991-1992	2013-2014
Norway	14	1991-1992	2010-2011
Switzerland	14	1991-1992	2013-2014
Turkey	14	1991-1992	2012-2013
Italy	11	1990-1991	2000-2001
Iceland	10	1990-1991	2013-2014
Ireland	8	1995-1996	2002-2003
Japan	8	1990-1991	2009-2010
Estonia	6	1990-1991	2001-2002
Luxembourg	6	1990-1991	1999-2000
Mexico	6	1999-2000	2007-2008
Poland	5	2006-2007	2013-2014
Germany	4	2006-2007	2013-2014
Chile	3	1990-1991	1994-1995
United Kingdom	3	1999-2000	2001-2002

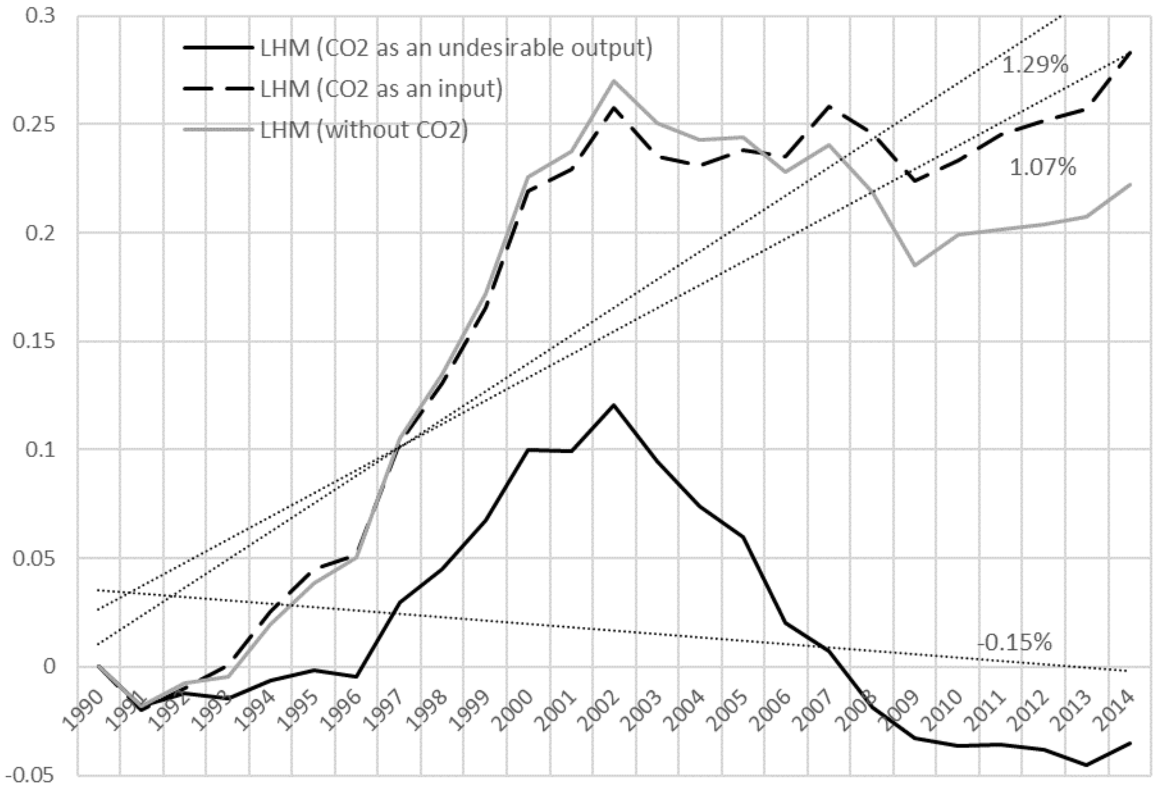

Figure 1. Dynamics in the cumulative average LHM productivity indicator for the whole group of the OECD countries based on different models for undesirable outputs, 1990-2014

Note: the stochastic annual rates of growth in TFP are given near the trend lines.

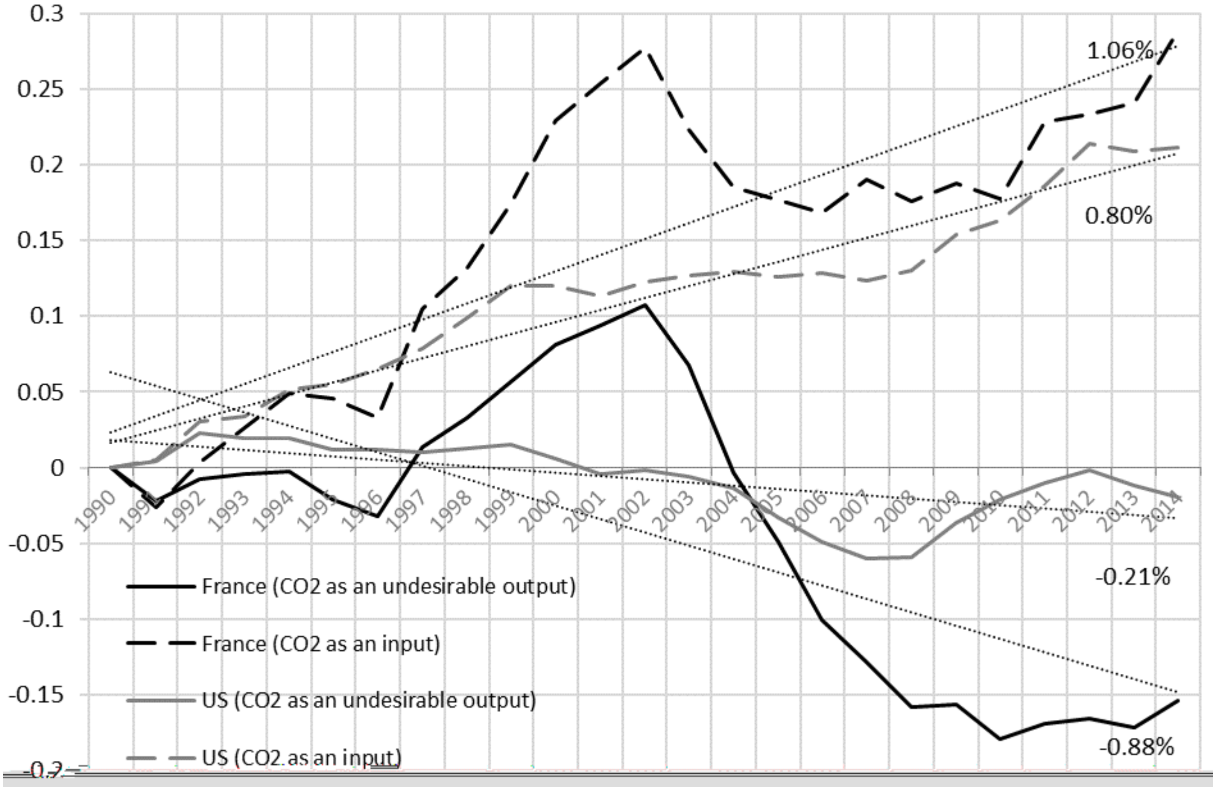

Figure 2. Dynamics in the cumulative average LHM productivity indicators for France and the US under the two models involving undesirable outputs, 1990-2014

Note: the stochastic annual rates of growth in TFP are given near the trend lines.

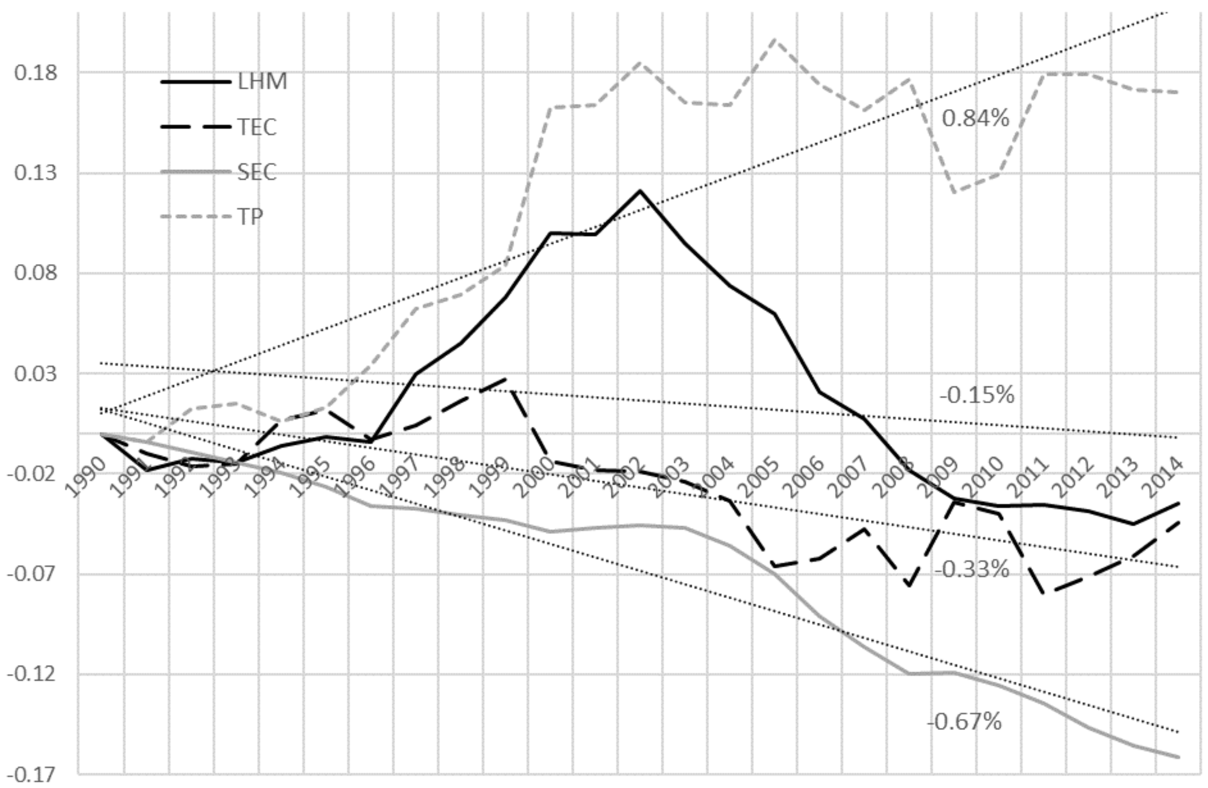

Figure 3. Decomposition of the cumulative average LHM productivity indicator based on the proposed approach, 1990-2014

Note: the stochastic annual rates of growth in TFP are given near the trend lines.